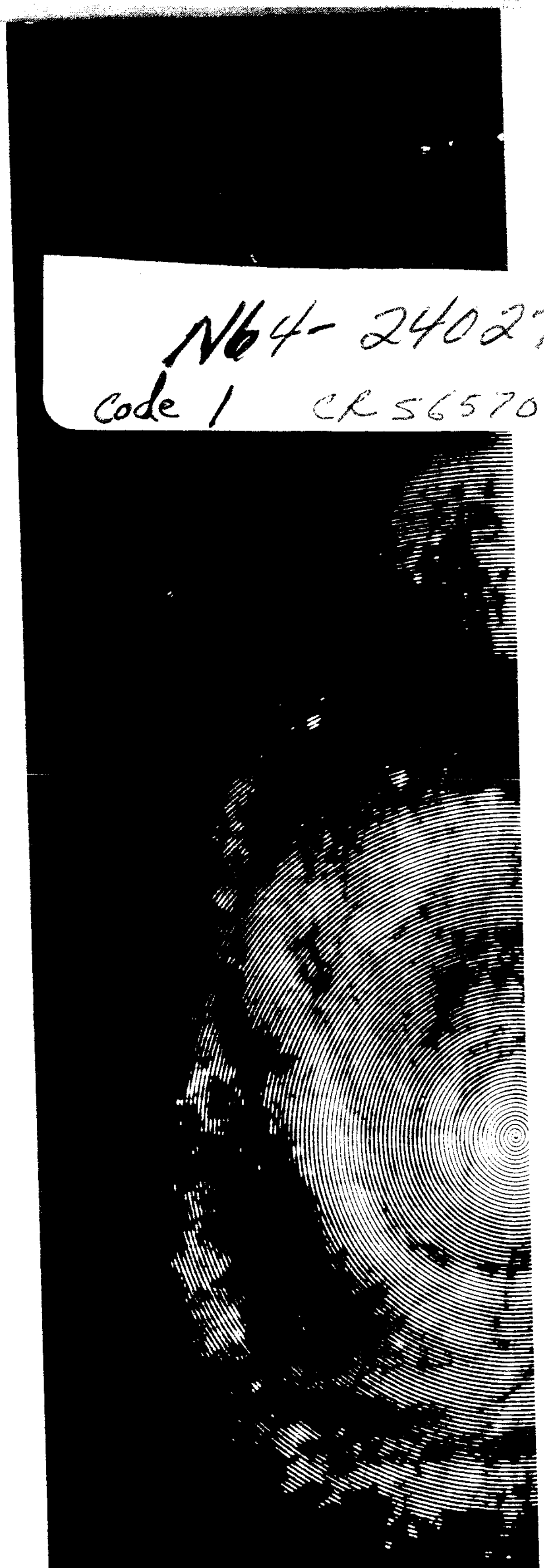


Report 111-F

DEVELOPMENT OF A PROTOTYPE 30-WATT TUNNEL DIODE INVERTER

Final Report
National Aeronautics and Space Administration
Contract NAS 5-2712
29 March 1963

ASTROPOWER, INC.
SUBSIDIARY OF THE DOUGLAS AIRCRAFT COMPANY, INC.

2121 PAULARINO AVENUE, NEWPORT BEACH, CALIFORNIA

Report 111-F

DEVELOPMENT OF A PROTOTYPE 30-WATT TUNNEL DIODE INVERTER

Final Report
National Aeronautics and Space Administration
Contract NAS 5-2712
29 March 1963

Prepared By
Dr. R. E. Smith
and
Mr. W. A. Bierley

ASTROPOWER, INCORPORATED
Newport Beach, California

ABSTRACT

2 4027

Procedures have been developed for the construction of a low voltage, high current inverter using tunnel diodes. A prototype tunnel diode inverter has been delivered to Goddard Space Flight Center. This inverter used eight 100-amp peak current tunnel diodes as switches, with four diodes operating in parallel as one switch. The inverter delivered produced 22.5 w of output power at 50 v rms, with a frequency of 50 cycles/sec, when driven by a 0.25-v d-c voltage source. At this output the efficiency was 20%; efficiencies of 42%, compared with a theoretical figure of 49%, were obtained at the 100-amp input level. It is anticipated that improved performance can be obtained at the 400-amp input level in future inverters, and that the input current of the inverter could conceivably be raised to the 1000-amp level. Author

FOREWORD

The work described in this report was conducted by Astropower, Inc. under National Aeronautics and Space Administration Contract NAS 5-2712, "Development of a Prototype 30-Watt Tunnel Diode Inverter." The program was administered by the Goddard Space Flight Center, Code 636.3, with Mr. Edward Pascuitti as Project Engineer.

The studies began in July of 1962 and were concluded in December of the same year. All work was performed in the Solid State Devices Laboratory of Astropower under the direction of Dr. Richard E. Smith, Head of the Laboratory, and the overall cognizance of Dr. G. Moe, Manager of the Research Division. Major technical contributions to the program were made by Mr. Wesley A. Bierley.

This report completes the work called for under Contract NAS 5-2712.

<u>TABLE OF CONTENTS</u>

LIST OF ILLUSTRATIONS

NOTE: All illustrations are bound in numerical order at the end of the report.

1.0 INTRODUCTION

The objective of the program described in this report was to perform applied research leading to the development of low voltage, high current tunnel diode inverters capable of handling useful amounts of power. A prototype inverter was to be fabricated, using commercially available tunnel diodes, and delivered to Goddard Space Flight Center. Inverter performance characteristics were to be determined by measurements on the completed inverter, and an engineering evaluation of the inverter was to be performed.

Earlier work at Astropower had shown (1) the technical feasibility of fabricating tunnel diode inverters using the then-available low current (0.2 amp) tunnel diodes, and (2) the possibility of constructing reasonably efficient high current inverters for operation with 0.25-v inputs in direct application to thermoelectric generators and photovoltaic cells. The use of the low voltage tunnel diode inverter in this application offered the possibility of producing a more reliable power system, since a lesser number of series converter cells was required to provide the operating voltage for the tunnel diode inverter than for transistor inverters. The degradation of any contact would not reduce the effectiveness of the direct energy converter as much in the low voltage tunnel diode system as in the higher voltage transistor system. In addition, the radiation resistance of the tunnel diode, the ability to operate over a larger temperature range, and the simplicity of the tunnel diode inverter circuits compared to those using transistors indicated a longer operating life for the power supplies when used in space environments.

The inverter consisted of two tunnel diodes and a transformer in a push-pull type of connection. If a square loop core was used in the transformer, a mode of operation existed where the frequency was basically determined by the flux linkages in the transformer as the core was driven from a negative to a positive flux saturation. The tunnel diodes operated as switches to reverse the sign of the voltage across the transformer. This inverter operated best in the low power/frequency range which was investigated in this program.

Contact with the manufacturers of tunnel diodes indicated that 100-amp tunnel diodes would be available during the contemplated time of this contract. These units made the 30-w level seem a reasonable goal, both from the aspect of handling useful power levels and that of performing the indicated engineering evaluation. Since an inverter of this type would be of considerable interest for space application, NASA Goddard Space Flight Center contracted to support a program at Astropower to determine the practicability of such a device, define its operating characteristics, and evaluate its potential application with direct energy conversion systems. The body of this report describes the experimental approach to the construction of this inverter, the theory of circuit operation, the results obtained, and the conclusions reached as a result of this program.

2.0 DESCRIPTION OF TUNNEL DIODE INVERTER

The tunnel diode inverter shown in Figure 1 was delivered to Goddard Space Flight Center. This inverter used eight RCA 100-amp tunnel diodes as switching elements, four in parallel acting as one switch. The transformer (shown in Figure 2) had a CRA-65 toroid core with a 5-in. outside diameter and a 4-in. inside diameter. The core was formed from "Supersil" steel 1 in. wide and 0.012-in. thick.

The eight-turn, center-tapped primary used 152 strands of No. 15 wire to carry the heavy current. Figures 3 and 4 show the details of the primary wiring and of the physical mounting of the inverter. The paralleling procedure for the tunnel diodes shown in Figure 3 was used to minimize the voltage drop in the connecting bus bars and to obtain a symmetrical current distribution around the core. The secondary had 1500 turns of No. 22 wire to achieve 50 v rms and was layer-wound over the primary.

2.1 Theory of Operation

The basic circuit of the self-oscillating tunnel diode inverter, shown in Figure 5, consists of two tunnel diodes and a square loop core with a center-tapped primary. It is convenient to approximate the square loop core by the characteristics shown in Figure 6a; the tunnel diodes will be represented by their static curves, shown in Figure 6b. The battery voltage is adjusted to lie somewhere on the negative resistance portion of the tunnel diode characteristic.

2.2 Graphical Approach

A simple graphical approach can be used to understand the operation of this circuit. When switch S (Figure 5) is closed, the current begins to flow in both tunnel diodes. If the circuit were completely symmetrical, the battery current would divide evenly and the inverter would not function. However, there is always some unbalance, either because of the slight difference in the tunnel diode characteristics or because the core has a residual flux density. Assume now, for ease of understanding, that there is no load across the secondary, that the core was left saturated at $-B_{sat}$ (point 1 in Figure 6a), and that tunnel diode No. 2 has exceeded its peak current rating and has switched to its high voltage state (called state 2 in the remainder of this report).

If it is now assumed that the core requires no magnetizing current, then the voltages across the tunnel diodes will adjust so that both tunnel diodes will lie along the same current line (see Figure 7). This location will be such that voltage V_1 (the battery voltage) will be the average of the voltages across each tunnel diode labeled V_{td1} and V_{td2}. This in turn will mean that a voltage difference $V_{td2} - V_{td1}$ will occur across the core with such a polarity that the flux will increase positively with time, and the core will move from point 1 on the BH curve to point 2, where it will saturate. When the core saturates, the current in tunnel diode No. 1 will increase, since V_1 will now be greater than V_{td1} (and in fact greater than the peak voltage of tunnel diode No. 1); but the current in tunnel diode No. 2 will decrease, since the valley voltage of this diode will be greater than the voltage V_1 (see Figure 7). This increase and decrease in the current will continue until both tunnel diodes switch, tunnel diode No. 1 going from its low voltage state to its high voltage state while tunnel diode No. 2 goes from its high voltage state to its low voltage state. When this switch occurs, the voltage across the core is reversed, and the core flux decreases with time until it saturates in the other direction. This change in flux in the transformer primary produces a square wave of voltage in the secondary, and since the switching action is determined by the switching speed of the tunnel diodes (which is very fast), a square wave is produced as shown in Figure 7b.

The actual requirement of the core for magnetizing current is met by a simple shift in the current flowing through the tunnel diode. Tunnel diode No. 1 moves up along its low voltage state to a higher current, and tunnel diode No. 2 moves down. If the load is applied to the secondary, the current in tunnel diode No. 1 increases further, while that of tunnel diode No. 2 decreases. This current difference, multiplied by the transformer turns ratio, appears as the output current.

It is now clear that the most judicious choice of battery voltage is that value which makes the no-load current the mean of the peak and valley currents of the individual tunnel diodes. If the load resistor is reduced (i.e., if the primary current is increased) to that value where either one of the tunnel diodes exceeds the peak or the valley current (one may occur before the other), then the circuit stops oscillating or changes to a very fast mode. This cannot damage either of the tunnel diodes, since the battery voltage is in the negative resistance portion, and thus the circuit requires no short circuit protection. Furthermore, if the voltage of the battery exceeds the valley voltage of either tunnel diode, the circuit stops oscillating and is not damaged unless excessively high voltages are applied.

2.3 Quantitatave Analysis

2.3.1 Frequency and Output Voltage

The graphical approach indicated above can be extended to make some predictions of efficiencies, voltages, etc., but a more complete analysis can be made if the tunnel diode is linearized as shown in Figure 8. Now condition 1 can be represented by a simple resistance, and condition 2 by a battery in series with a resistor. The equivalent circuit for the inverter under the conditions indicated previously (core saturated in a negative direction, no-load conditions, and B-H curve as shown in Figure 6) is shown in Figure 9.

An analysis of this circuit, using Kirchhoff's Law, Ampere's Circuital Law, and Faraday's Law leads to the equations given in Table I for the current in each tunnel diode, the current into the circuit, the frequency, and the voltage output.

The equations for the current in each tunnel diode indicate the shift (discussed above) in the tunnel diode current required by the magnetizing current of the core, and these equations show that for proper design

$$\frac{Hl}{N} < \begin{cases} \dfrac{2V_1 - V_o}{R_2} \\ \dfrac{2V_1 - V_o}{R_1} \end{cases} \qquad \text{Condition 1}$$

In practice this is not difficult to do, since in general

$$\frac{Hl}{N} << \frac{i_p - i_V}{2} \qquad \text{Condition 2}$$

and our experience indicates that invariably Condition 2 assures Condition 1.

TABLE I

COMPARISON OF CHARACTERISTIC EQUATIONS FOR LOADED AND UNLOADED TUNNEL DIODE INVERTERS

Characteristics	Unloaded Tunnel Diode Inverter	Loaded Tunnel Diode Inverter
Instantaneous i_1 current in TD No. 1	$i_1 = \frac{2V_1 - V_o}{R_1 + R_2} + \frac{Hl}{N} \frac{R_2}{R_1 + R_2}$ (1)	$i_1 = \frac{2V_1 - V_o}{R_1 + R_2} \frac{1 + \frac{V_1 R_2}{(2V_1 - V_o)R'}}{1 + \frac{R''}{R'}}$ (10)
i_2 current in TD No. 2	$i_2 = \frac{2V_1 - V_o}{R_1 + R_2} - \frac{Hl}{N} \frac{R_1}{R_1 + R_2}$ (2)	$i_2 = \frac{2V_1 - V_o}{R_1 + R_2} \frac{1 + \frac{V_1 - V_o}{2V_1 - V_o} \frac{R_1}{R'}}{1 + \frac{R_1 R_2}{R_1 + R_2} / R'}$ (11)
i_t battery current	$i_t = 2\left[\frac{2V_1 - V_o}{R_1 + R_2}\right] + \frac{Hl}{N} \frac{(R_2 - R_1)}{R_1 + R_2}$ (3)	$i_t = \frac{2V_1 - V_o}{R_1 + R_2} \frac{2 + \frac{V_1(R_1 + R_2) - V_o R_1}{(2V_1 - V_o)R'}}{1 + \frac{R''}{R'}}$ (13)
i_e load current		$i_e = \frac{\frac{N_2}{N_1}\left[V_1(R_2 - R_1) + V_o R_1\right] / R_1 + R_2}{\left(\frac{N_2}{N_1}\right)^2 R'' + R_s + R_L}$ (12)
F (frequency) cycles/sec	$F = \frac{\frac{V_1(R_2 - R_1)}{R_1 + R_2} + \frac{V_o R_1}{R_1 + R_2} - \frac{Hl}{N} \frac{R_1 R_2}{R_1 + R_2}}{4\varphi_s N \times 10^{-8}}$ (4)	$F = \frac{\frac{V_1(R_2 - R_1)}{R_1 + R_2} + \frac{V_o R_1}{R_1 + R_2}}{4\varphi_s N\left[1 + \frac{R''}{R'}\right] \times 10^{-8}}$ (14)
E_o open circuit output volt	$E_o = \frac{N_2}{N_1} \frac{V_1(R_2 - R_1) + V_o R_1 - \frac{Hl}{N} R_1 R_2}{R_1 + R_2}$ (5)	

In these equations R_1 is the sum of the resistance of the tunnel diode plus the wiring resistance of the circuit, R_2 is the sum of the resistance of tunnel diode No. 2 in state 2 plus the wiring resistance of that circuit, $R'' = \frac{R_1 R_2}{R_1 + R_2}$, and $R' = (R_S + R_L)\left(\frac{N_1}{N_2}\right)^2$

It is also interesting to note that while an unbalance is necessary for the circuit to start, it is desirable to have R_1 as close to R_2 as possible. This reduces the equations for frequency, output voltage, and input current to the simple forms shown below and - perhaps more important - makes the time and output voltage independent of the input voltage variation over a large portion of the operating range of the circuit.

$$F = \frac{V_o}{8\varphi_s N \times 10^{-8}} \tag{6}$$

$$E_o = \frac{1}{2}\frac{N_2}{N_1} V_o \tag{7}$$

$$i_T = \frac{2V_1 - V_o}{R_1} \tag{8}$$

Notice also that the input current, and thus the input power, is independent of the magnetizing current. This does not mean that the current does not exist, only that the increase in current above the value for no magnetizing current through tunnel diode No. 1 is exactly balanced by the decrease of current through tunnel diode No. 2.

Since the current in each tunnel diode is limited to the peak and valley currents, it is also possible to solve for the voltage which should make this circuit operate. This condition is given in Equation 9 with the assumption that the magnetizing current is small compared to the peak and valley current:

$$\frac{i_v (R_1 + R_2) + v_o}{2} < v_1 < \frac{i_p (R_1 + R_2) + v_o}{2} \tag{9}$$

2.3.2 Efficiency of Inverters

It is possible to calculate the efficiency of the inverter using the linearized model described earlier. If a load is placed across the secondary, then Equations 1 through 5 (given in Table 1) are modified, resulting in Equations 10 through 14 in Table I.

An examination of Equations 5 and 12 indicates that the output current can be written as:

$$i_e = \frac{E_o}{\left(\frac{N_2}{N_1}\right)^2 \frac{R_2 R_1}{R_1 + R_2} + R_S + R_L} \tag{15}$$

This in turn means that the output resistance (R_{out}) of the tunnel diode inverter can be written as

$$R_{out} = \left(\frac{N_2}{N_1}\right)^2 \frac{R_2 R_1}{R_1 + R_2} + R_S \tag{16}$$

since this is nothing more than the equation of a battery and two resistances in series. The output power can now be simply written as

$$P_{out} = \frac{E_o^{\,2} R_L}{(R_{out} + R_L)^2} \tag{17}$$

and the input power, while a little more complicated, has the form shown below:

$$P_{in} = v_1 \left(\frac{2v_1 - v_o}{R_1 + R_2}\right) \frac{2\left(1 + \frac{1}{2}\left[\frac{(R_1 + R_2) v_1 - v_o R_1}{R'}\right]\right)}{\frac{1 + R''}{R'}} \tag{18}$$

Finally, this leads to the following expression for efficiency:

$$E_{ff} = \frac{E_o^{\,2} R_L (R_1 + R_2) \frac{(1 + R'')}{R'}}{(R_o + R_L)^2 v_1 (2v_1 - v_o)^2 \left[1 + \frac{1}{2} \frac{(R_1 + R_2) v_1 - v_o R_1}{R''}\right]} \tag{19}$$

Here again, if the circuit is assumed to be balanced, these equations may be reduced to extremely simple forms, as shown below.

$$F = \frac{v_o}{8\varphi_s N \times 10^{-8}} \left(\frac{1}{1 + \frac{R}{2R'}}\right) \tag{20}$$

$$P_{in} = \frac{v_1 (2v_1 - v_o)}{R} \tag{21}$$

$$E_{ff} = \frac{\left(\frac{N_2}{2N_1}\right)^2 v_o^2 R_L R}{(R_L + R)^2 \, 2v_1 (2v_1 - v_o)}$$

$$= \frac{\left(\frac{N_2}{2N_1}\right)^2 R_L v_o^2 R}{(R_L + R)^2 \, 4v_1 (v_1 - \frac{v_o}{2})} \tag{22}$$

One must exercise care in using the last equation to calculate the efficiency for this circuit. It is evident in this equation that if the battery voltage is made equal to $v_o/2$, an infinite efficiency results. This is, of course, physically impossible, but it results because no restraints were placed on the location of the tunnel diodes along the linearized curves. This solution corresponds to operation at points A and A' as shown in Figure 8, or an operating point when the tunnel diodes would have no current flowing, and therefore, another approach is desirable to calculate the efficiencies of this circuit. Nevertheless, the linear model is useful in predicting the operation of the tunnel diode inverter over a large portion of its operating range, but not for calculating maximum efficiency.

It is quite easy to determine where the maximum efficiency can be expected for any physically realizable tunnel diode. If no load is placed on the inverter and a stable inverting operation is achieved, then the two tunnel diodes require roughly the same current, differing only by the amount necessary to supply the magnetizing current. If a load is applied to the output, then these operating points shift further apart in current, and the output voltage stays approximately the same. The maximum power into the load, and therefore the maximum efficiency, occurs when the "on" tunnel diode operates at its peak value and the "off" tunnel diode operates at its valley point. The efficiency is then given by Equation 23:

$$\eta = \frac{\left(\frac{I_p}{I_v} - 1\right)\left(\frac{V_v}{V_p} - 1\right)}{\left(\frac{I_p}{I_v} + 1\right)\left(\frac{V_v}{V_p} + 1\right)} \tag{23}$$

where $I_p V_p$ represents the peak points and $I_v V_v$ the valley points for the tunnel diodes used. Hanrahan* has shown that if the magnetizing current is included, then this expression is modified to

$$\eta_o = \left(1 - \frac{I_m}{\Delta I}\right) \eta \qquad (24)$$

where $\Delta I = (I_p - I_v)$. He has also shown that the efficiency for a sinsoidal output is given by:

$$\eta_1 = \frac{8}{\pi^2} \left(1 - \frac{I_m}{\Delta I}\right) \eta_o$$

Equation 23 has application to other tunnel diode inverter and converter circuits which use the diodes as switches. Figure 10 shows some possible circuit variations: the single tunnel diode converter using a linear core, a push-pull converter, and a push-pull converter using a square loop core.

Figure 11 is a plot of Equation 23 in terms of the peak-to-valley-voltage ratio of the available tunnel diodes, and the peak-to-valley-current ratio. It is now possible to specify the minimum peak-to-valley ratios for any diodes to establish any desired efficiencies. For example, to obtain a theoretical 75% efficiency, any combination of diode properties above the line in 23 will permit this goal to be reached. A possible combination is $I_p/I_v = 12$, $V_v/V_p = 20$. It is also possible now to calculate the maximum efficiency to be expected for the inverter in terms of the peak-to-valley ratios of any given tunnel diodes.

2.4 Tunnel Diodes Used in Inverter

There are three types of tunnel diodes available commercially: germanium, silicon, and gallium arsenide. Calculations of theoretical efficiencies of inverters using data from the units commercially available indicated that the low current silicon units had a maximum efficiency of about 50%, while germanium and gallium arsenide units attained about 60%. Information supplied by RCA indicated that the maximum efficiency they expected to reach with both

*Hanrahan, D. J., "Analysis of a Tunnel-Diode Converter Performance," IRE Trans. on Electron Devices, E9-9, No. 4 (1962) p 358.

germanium and gallium arsenide was 65%. Germanium units were commercially available with a 20-amp peak current and could be fabricated with a 100-amp peak current rating with a measured efficiency of 45 to 49%. The junctions themselves had a higher efficiency than this, but the package produced about a 6% loss in the measure efficiency.

The operating input voltage of the typical germanium tunnel diode inverter is 0.25 v. If 30 w is the desired output power, then for 100% efficient operation the peak current of the diodes should be rated at 120 amp, and if the efficiency falls to 25%, the input current should then be 480 amp. Tunnel diodes can be produced with peak currents as high as 1000 amp, but the package required to house these units requires a special design. The quoted delivery time on units larger than 100 amp was almost four months, and this prevented their use in the program. Eight 100-amp units were ordered in place of two 400-amp units with measured efficiencies between 45 and 49%.

2.5 Transformer Design

In order to achieve maximum efficiency with this inverter, it was necessary to minimize core and copper losses in the circuit. The circuit configuration shown in Figure 3 was chosen to minimize the voltage drop in the connecting bus bars. A common design criterion for transformer windings is 700 circular mils per amp. Because of the importance of minimizing joule heating loss, this transformer was designed with 1200 circular mils per amp. This figure should be higher, but 152 strands of No. 15 wire became difficult to wind around a toroid.

The frequency of the inverter was basically determined by the 1/NBA product indicated in Equation 6. The flux density was, of course, determined by the material, and the choice was made so that a minimum hystersis loss resulted. Experiments were run with the 100-amp units to determine guidelines for the minimum number of turns (and therefore the minimum length of wire) that could be used with successful switching.

A primary of eight turns was chosen as a result of these experiments. The tunnel diode's switching time is extremely short compared to the frequencies ordinarily used in power work, but the switching times of the inverter circuit are not short compared to the higher power frequencies. More will be said of this phenomenon later. This limitation on switching speed made it desirable to operate the inverter at approximately 60 cycles, and the core area was chosen to obtain this frequency. The secondary was layer-wound with No. 22 wire to produce 50 v rms. Fifteen hundred turns were required to achieve this voltage.

3.0 EXPERIMENTAL PROGRAM

3.1 Experiments with 1-Amp Unit

Early in the program, experiments were performed using the readily available 1-amp tunnel diodes to determine if an efficient inverter could be developed at this current level with diodes of 45 to 49% efficiency. The results are shown in Figure 12. The maximum efficiency obtained was approximately 42% with 0.23 v input. This inverter operated over the voltage range of 0.22 to 0.30 v, with various core cross-sectional areas, over the frequency range from 30 to 400 cycles/sec. Tests were also run to check the operation of tunnel diodes in parallel; one of the cores wound for the 1-amp units was used. The results of the test are shown in Figure 13. The drop in maximum efficiency from 42 to 35% was caused by the increased copper loss. It was also experimentally demonstrated that it is possible to operate the tunnel diodes in a series circuit if the circuit shown in Figure 13 is used.

3.2 Experiments with 100-Amp Units

The 100-amp units were used to make several inverters to gain further insight into the problems to be expected when operation at the 400-amp level was attempted. Figures 15, 16, and 17 show the results obtained with these inverters. As predicted in our analysis, and as shown in Figure 15, the input current and the output voltage remained practically constant as the load was changed. The energy that was absorbed in the "off" diode was shifted to the load as the load current was raised, until a threshold operation was obtained where the inverter shifted modes. This inverter operated at about 180 cycles/sec and produced an 8-v output.

Figure 16 indicates the sensitivity of this inverter to copper loss. The number of turns was increased in a second transformer design, thereby decreasing the magnetizing current, but the wire size was decreased from a design of 1400 circular mils/amp to 715 circular mils/amp. This decrease in wire size reduced the maximum efficiency from 42% to 25%, although the operation of the inverter was basically the same.

Figure 17 photographically displays the operation of the tunnel diode inverter and indicates the switching problem mentioned earlier. Figure 17a shows the open circuit output voltage. Notice the notch in the curve when the tunnel diodes were switching. This notch occurred because one tunnel diode switched before the other. When this happened, a large current was drawn from the power supply as shown in Figure 17d, and a symmetrical situation existed in the inverter. After a delay, which in the photograph is about 3.2% of the square wave period, the second tunnel diode switched. The mechanism for controlling this delay time is not understood at this time. It is known that this switching time is a function of the input voltage and the load resistance. Figure 17b shows the same inverter operating under identical conditions, except that load for maximum efficiency (matched conditions) was applied. Notice that the notch here is shorter than it was when the inverter was open-circuited. This shortening continued as the load resistance was reduced, until the inverter stopped operating at the so-called "threshold point."

The maximum efficiency for this inverter did not occur at this threshold point as predicted by theory. In fact, Figure 17c gives some rather interesting results with regard to the operating voltage of the diodes at this point of maximum efficiency. The "on" diode was operating at about 50 mv and the "off" diode at about 0.4 v. The static characteristic curve of these diodes is shown in Figure 18, with these operating points indicated. If the inverter was loaded beyond this point, so that Point A moved up towards the peak current point, then the input voltage across the transformer decreased, and this decrease more than offset the gain in current differential that could exist between the peak current and the valley current of the diode pairs.

The operation of this single diode pair with the production of 8 w of output power indicated that four diode pairs, with proper transformer design, should produce 30 w of output power.

3.3 Experiments at the 400-Amp Input Level

It was necessary to design the transformer for the prototype 30-w inverter without the benefit of a breadboard model because of delays in the delivery of the eight tunnel diodes required for its operation. When the units arrived, they were inserted in their heat sinks, and the inverter was operated. (The package and design of this inverter have already been discussed in Section 2.0.) The results of tests of the inverter are shown in Figure 19. The efficiency was lower than that obtained for the 8-w inverter, and consequently the output power never quite reached the 30-w level. The maximum power achieved was 22.5 w. During the last test, it was noted that one tunnel diode (No. 7) was considerably cooler than the others. This might indicate that some of the diodes had degraded as a result of use in this inverter. Earlier in the program, a 20-amp tunnel diode degraded after a short period of use, and the peak-to-valley current ratio became so low that the inverter stopped functioning.

The notched effect also appeared, with four distinct steps occurring. Figure 20 shows this effect on the voltage across one of the tunnel diodes. The fast oscillation at the end of the high voltage "off" operation indicates that this diode was switching several times before the core finally switched completely.

4.0 PERFORMANCE CHARACTERISTICS OF THE TUNNEL DIODE INVERTER

4.1 Major Characteristics

Table II lists some important performance characteristics of the tunnel diode inverter as determined by our experiments at the three input levels used.

TABLE II

INVERTER PERFORMANCE CHARACTERISTICS

Input Current (Amp)	Maximum Efficiency, %	Maximum Power, w	Frequency Regulation, %	Voltage Regulation, %
1	40	0.1	17	50
100	41	8.0	17	50
400	20	22.0	11	55

The inverter delivered operated at 40 cycles/sec. Because of the switching problems, it was not considered practical to operate this type of inverter at frequencies above 100 cycles/sec; a lower frequency than 40 cycles/sec would be desirable. The frequency regulation of the inverter was basically affected by the winding resistance of the primary and the nonlinearity of the positive resistance portion of the tunnel diode. Since the frequency of the inverter was determined by the volt-sec product input to the core, any factor which altered the voltage across the primary changed the frequency. This included source voltage variations and changes in the operating points of the tunnel diode as the load was applied to the secondary. It does not now seem possible to solve this problem easily, since the third terminal is not available on the diode, and since there is no ready way to couple into the primary circuit with an element that offers any amplification. Control could be achieved, but only at the further sacrifice of efficiency.

The output voltage of this inverter was 60 v rms at no load, but this could be altered by simply changing the turns ratio on the transformer.

Early tests on this unit were made using 20 v rms. The parameters that affect frequency regulation also control voltage regulation. The only way that voltage regulation can be improved is with the use of feedback circuits, and this cannot be accomplished easily with this inverter.

4.2 Source Requirements

These inverters require a source voltage of 0.25 v for operation. They will operate over the general voltage range from 0.22 to 0.30 v at the low input current levels, but at the 400-amp level this range was restricted from 0.23 to 0.26 v. The source resistance of this power supply must be below a specified limit, depending on the input current level, for the inverter to start. When the source is connected to the inverter, both diodes are in the low voltage state. The current from the source must rise until one of the diodes passes the peak voltage and switches. This requirement means that the power supply must be capable of delivering approximately twice the operating current without having a stable operating point within the positive resistance portion of the tunnel diode curve. If the open circuit voltage of the source is adjusted to the minimum input operating voltage, then the minimum source resistances for the three operating levels of 1 amp, 100 amp, and 400 amp become 0.065 ohms, 0.68 milliohms, and 0.18 milliohms, respectively.

If the voltage of the source was adjusted to the proper operating range and a switch was closed, no difficulty was experienced in starting the inverter. In fact, the inverter would start with source resistances larger than those indicated above; however, if the source voltage was raised slowly to the operating value, then it was necessary to meet the requirements given above. The reason is quite obvious if one considers the starting mechanism and the stable operating voltage range. Before the inverter started, both diodes were conducting, and as the source voltage was slowly raised, the current drawn from the source increased until approximately twice the peak current of the diode was drawn. Then one of the diodes switched, and the inverter started to oscillate. The source current then dropped to approximately one-half the previous value, and if this drop caused the source voltage to exceed the maximum operating voltage, the inverter would never start. This mechanism also made it difficult to restart the inverter if the source voltage dropped below the operating voltage level. The current suddenly doubled, and this tended to reduce the source voltage even more. At the other end of the scale, if the source voltage exceeded 0.30 v, the current dropped suddenly by a factor of 5, the source voltage rose and the inverter would not operate at all. Within the operating range of the inverter there was a stabilizing factor, however. As the source voltage dropped from its high value of 0.30 v, the current drawn from the source decreased, and this decrease tended to keep the source voltage within the operating range of the inverter.

This inverter, in contrast with other inverters, presented practically a constant current drain, which was roughly the peak current of the tunnel diode, on the power supply.

4.3 Discussion of Results

The efficiency of the inverter at the 400-amp input level was considerably lower than anticipated, while that at the 100-amp input level was close to that predicted by the theoretical analysis. The tests on the 400-amp unit indicated that the operating point of "off" diode was not shifted down towards the valley by increasing the load current as much as would be desirable to obtain efficient operation. With the smaller units (100-amp) the maximum efficiency was obtained with lower input voltages. The 400-amp unit could not be operated at a low enough input voltage to place the no-load operating point of the "off" diode near the valley point. A transformer redesign would undoubtedly improve the situation by permitting operation close to optimum conditions and by eliminating the switching delays that plagued the inverter. Additional work in this area would probably raise the maximum efficiency of the 400-amp inverter to the 40% range. Further increase in efficiency could only be expected as a result of basic work on producing tunnel diodes from new materials which have higher theoretical efficiencies.

The requirement for a low internal source impedance is not too demanding, since any source that provides 400 amp at a 0.25-v level must have a low internal impedance to supply any power and maintain this voltage. It is doubtful that tunnel diode inverters operating at current levels much larger than 400 amp will prove practical for application to any direct energy conversion system, since the distribution system for the source would be difficult to fashion for these high current levels.

5.0 CONCLUSIONS

The program undertaken at Astropower has developed the techniques required to fabricate a low voltage, high current tunnel diode inverter, and has determined some of the characteristics and problems associated with such a device. The performance characteristics of the test inverter were not as good as initial calculation had indicated were possible, but it is believed that significantly improved inverters can now be produced by taking advantage of the understanding of the inverter, the improved transformer design, and the technical skills developed during the course of this program.

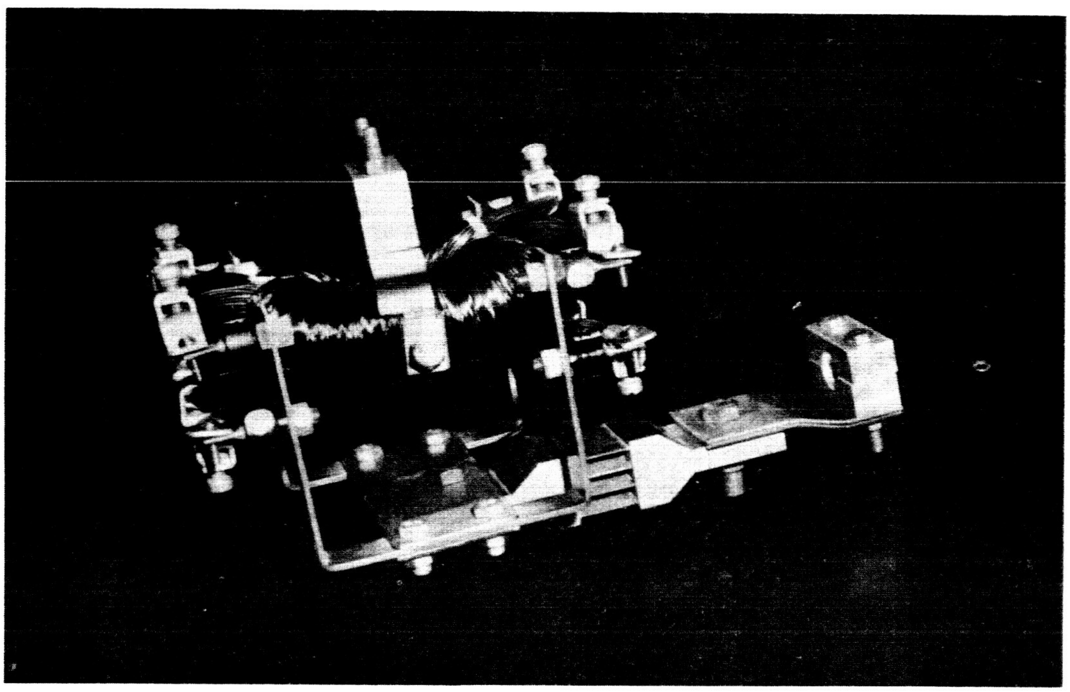


Figure 1. Photograph of Tunnel Diode Inverter

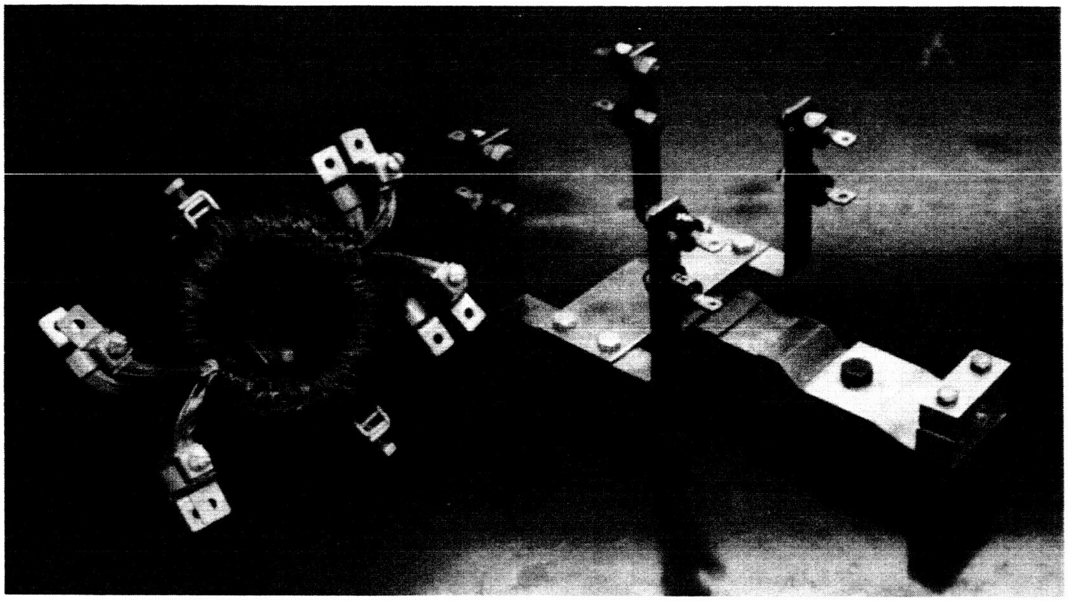


Figure 2. Photograph of Transformer and Tunnel Diode Interconnections

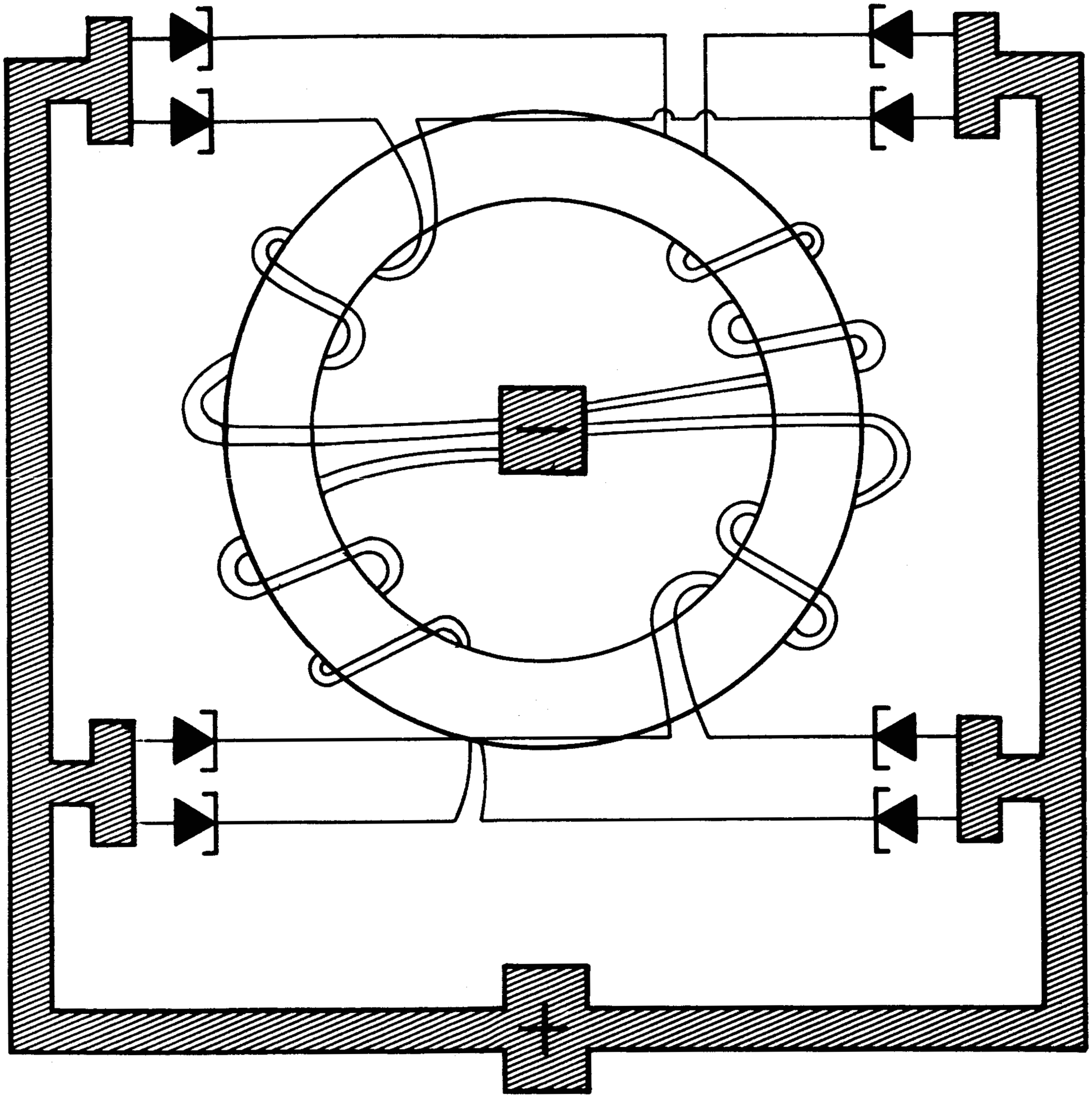


Figure 3. Wiring Diagram for Prototype Inverter

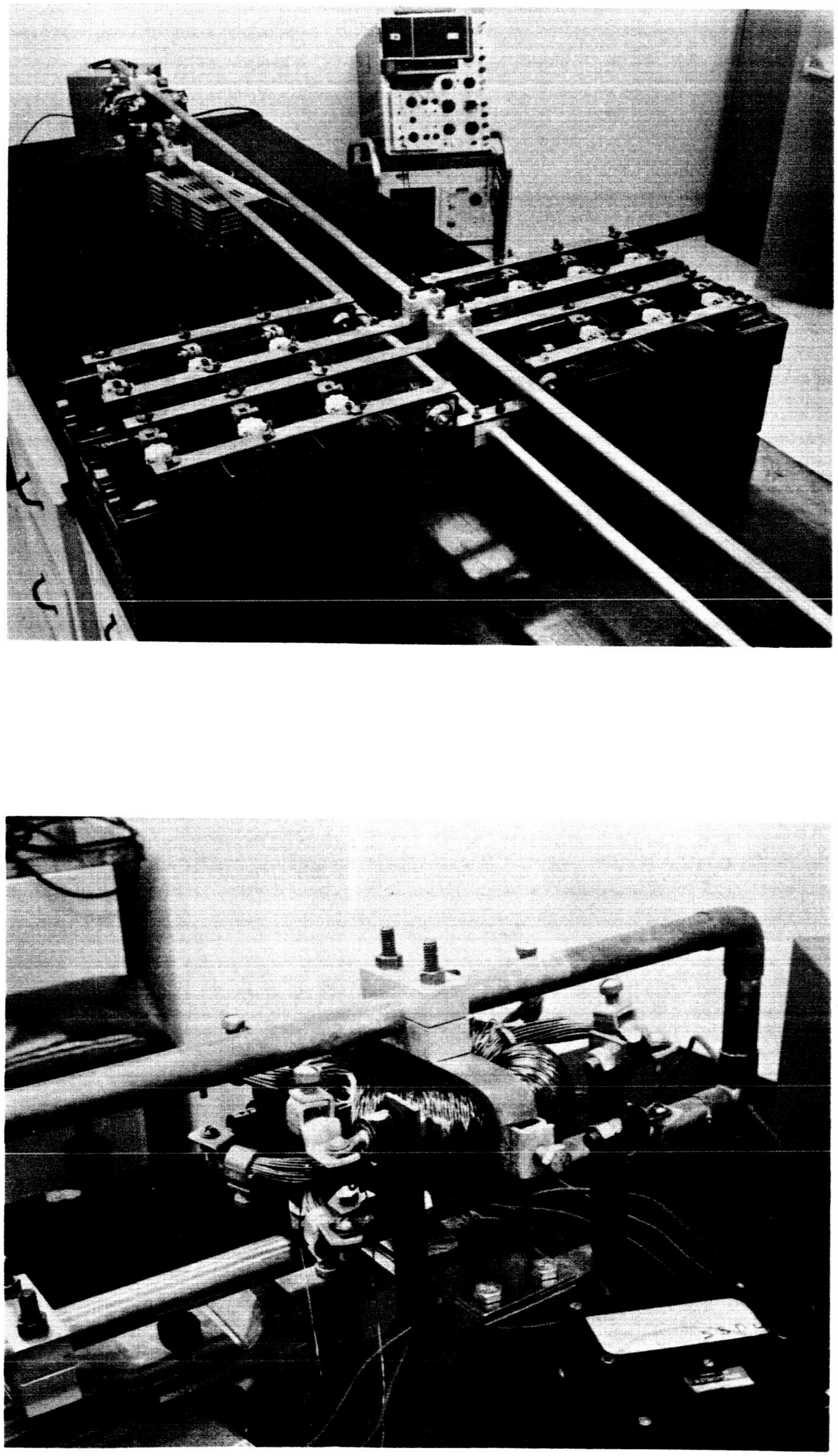


Figure 4. Photograph of Tunnel Diode Inverter in Place on Power Supply

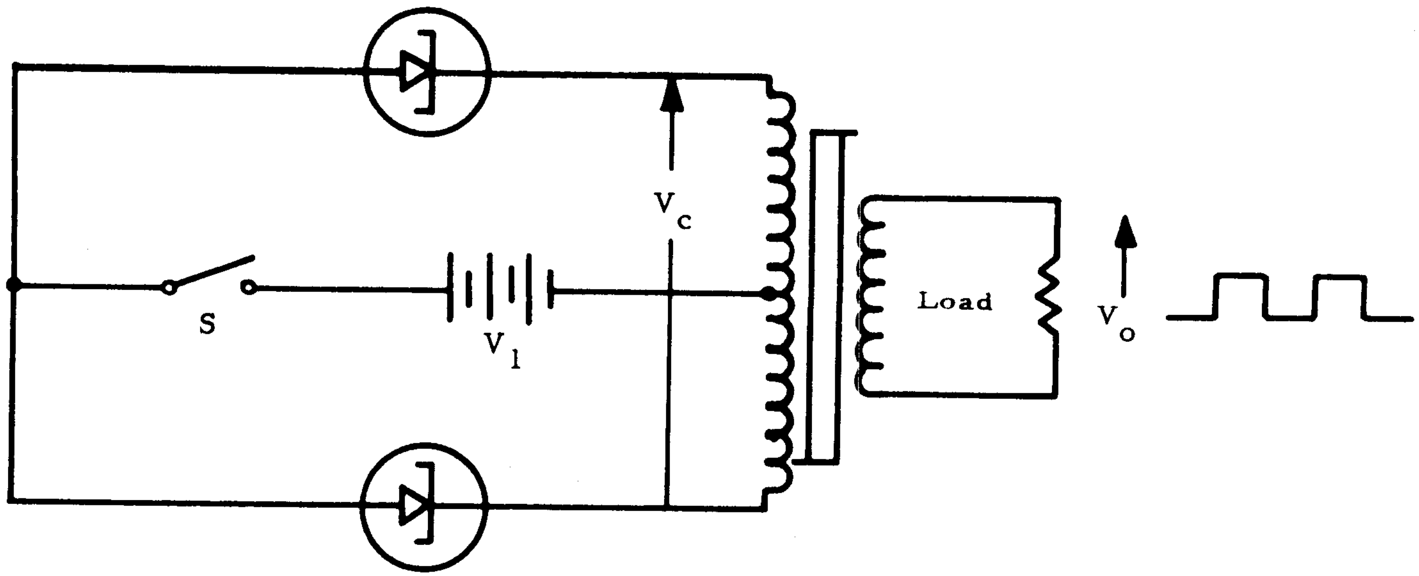


Figure 5. The Self-Oscillating Tunnel Diode Inverter

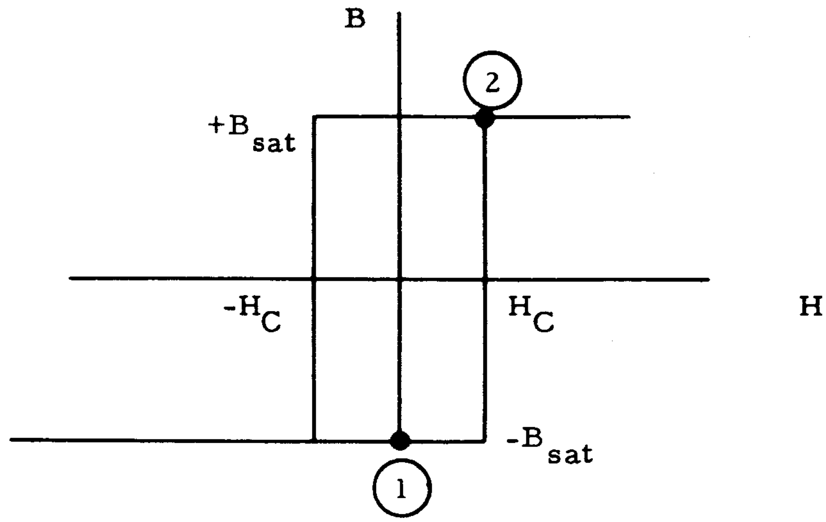


Figure 6a. B-H Approximation for the Core Used in the Self-Oscillating Tunnel Diode Inverter

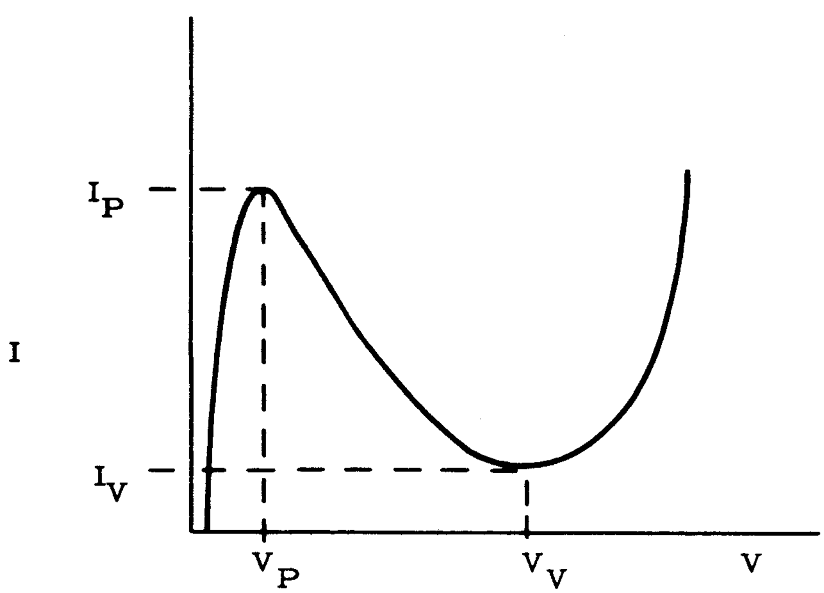
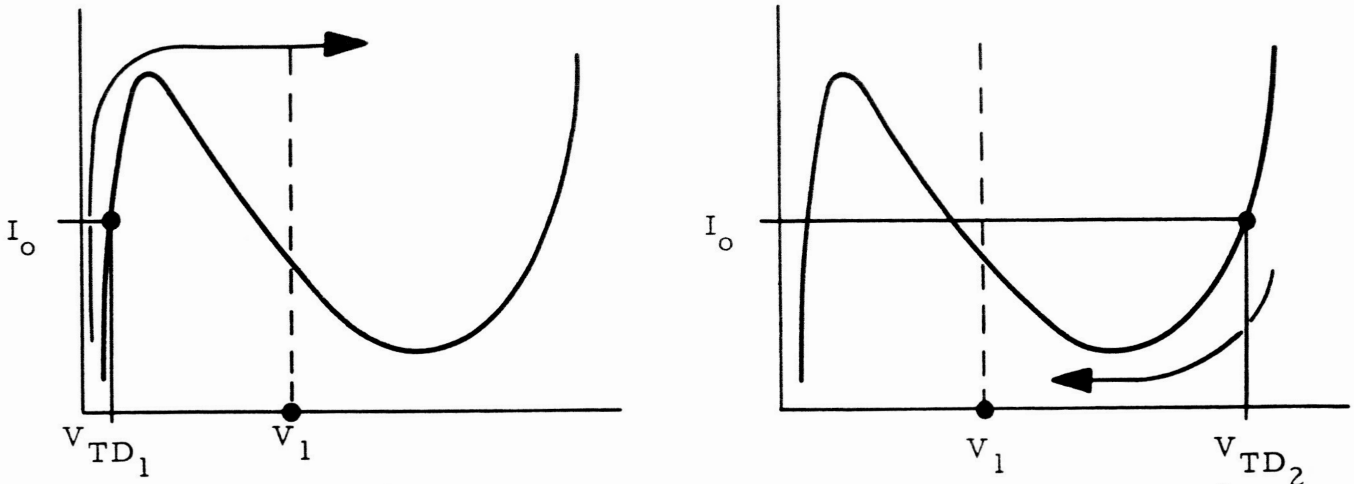
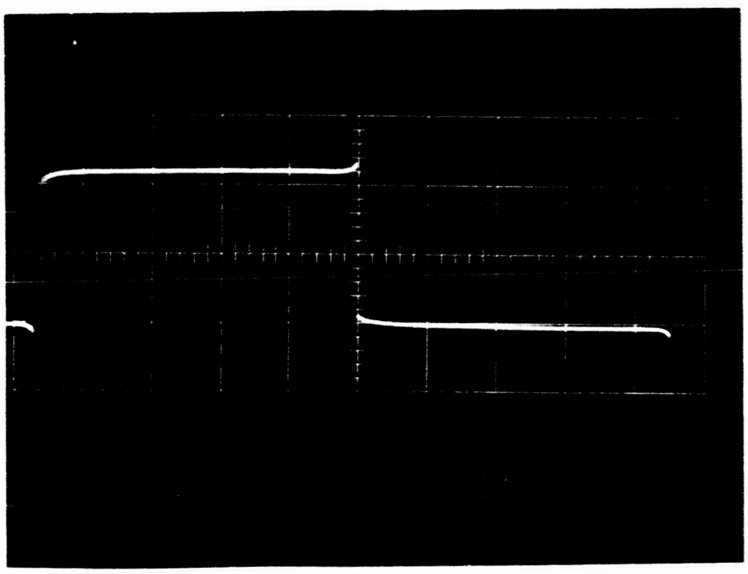


Figure 6b. Static Curves of the Tunnel Diode



Arrows Indicate Motions of Operating Points When Core Saturates

Figure 7a. Location of the Tunnel Diodes During the Time When the Core is Moving from $-B_{sat}$ to $+B_{sat}$, Assuming No Magnetizing Current



0.2V/cm

0.2MS/cm

Figure 7b. Output Waveform for Tunnel Diode Inverter

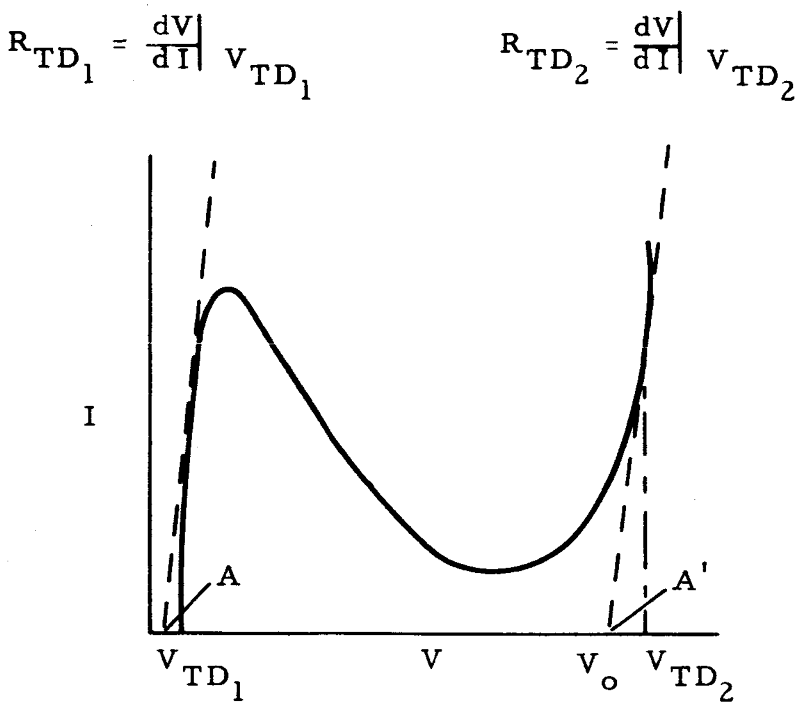


Figure 8. Linearization of the Tunnel Diode

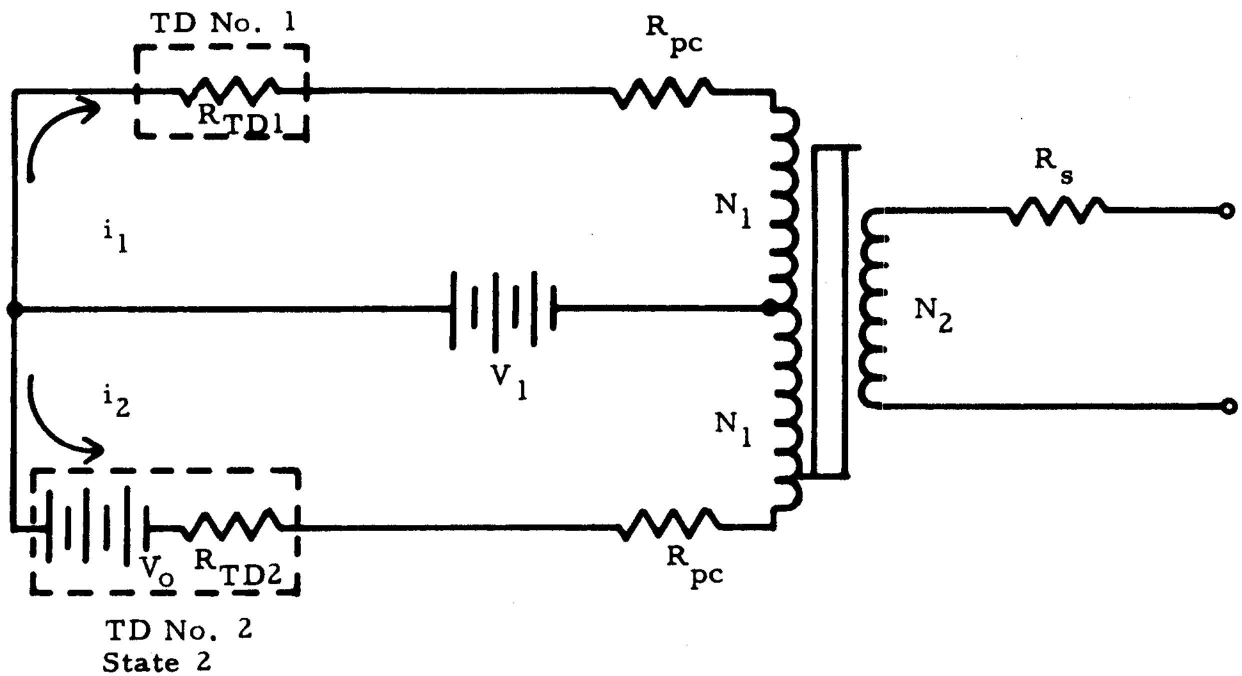
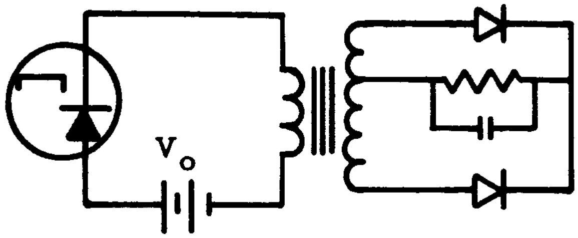
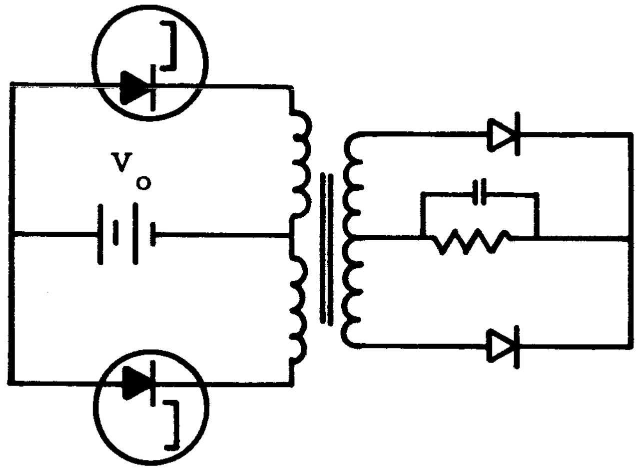


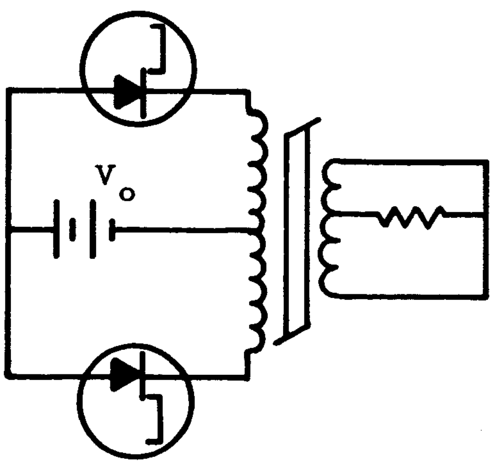
Figure 9. Equivalent Circuit of the Self-Oscillating Tunnel Diode Inverter During the Time the Core Moves from $-\varphi_{sat}$ to $+\varphi_{sat}$



a. Single Tunnel Diode Converter with Linear Core



b. Push-Pull Converter with Linear Core



c. Push-Pull Converter with Square Loop Core

Figure 10. Variations of the Tunnel Diode Converter

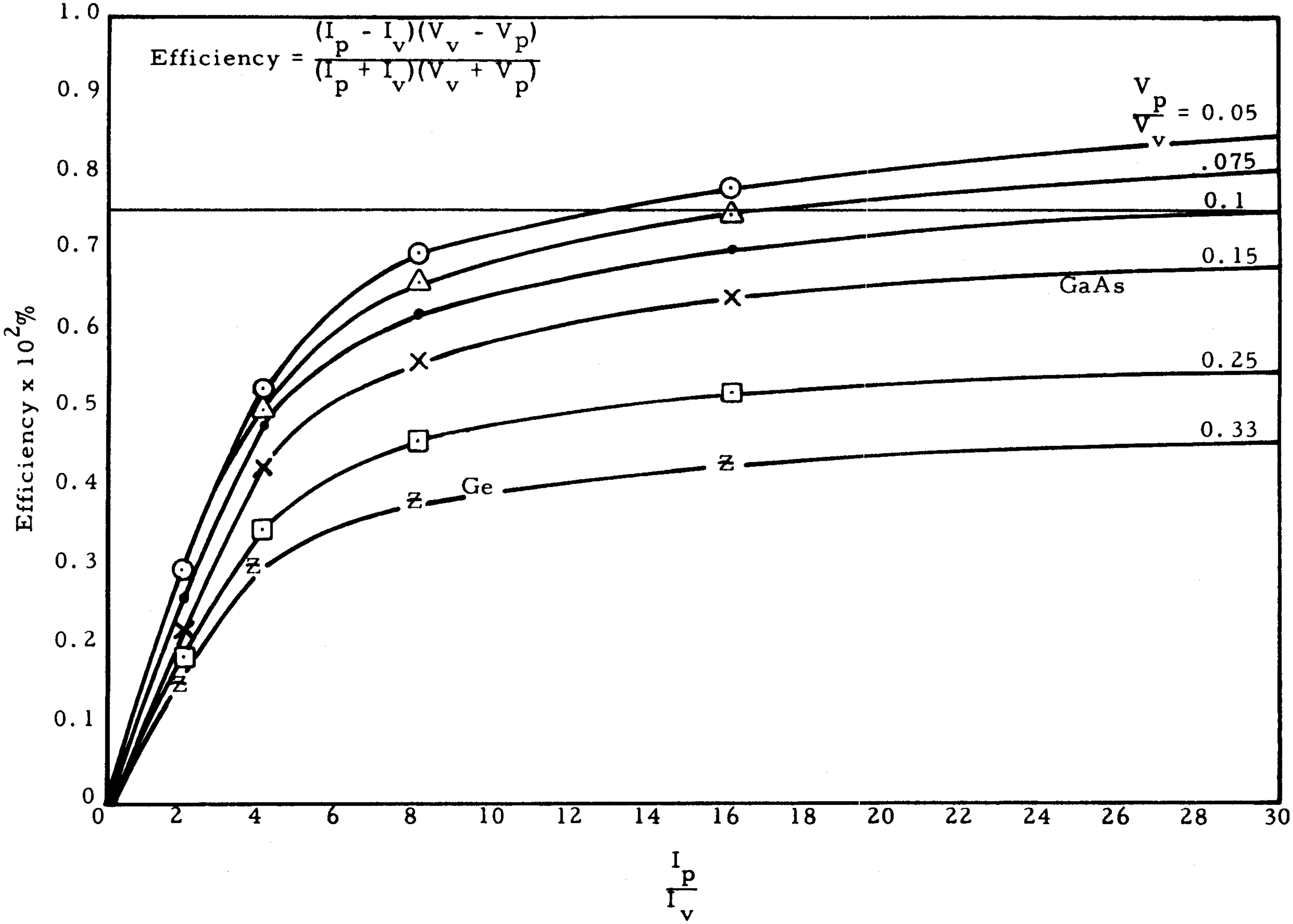


Figure 11. **Efficiency of the Push-Pull Tunnel Diode Converter with Square Loop Core**

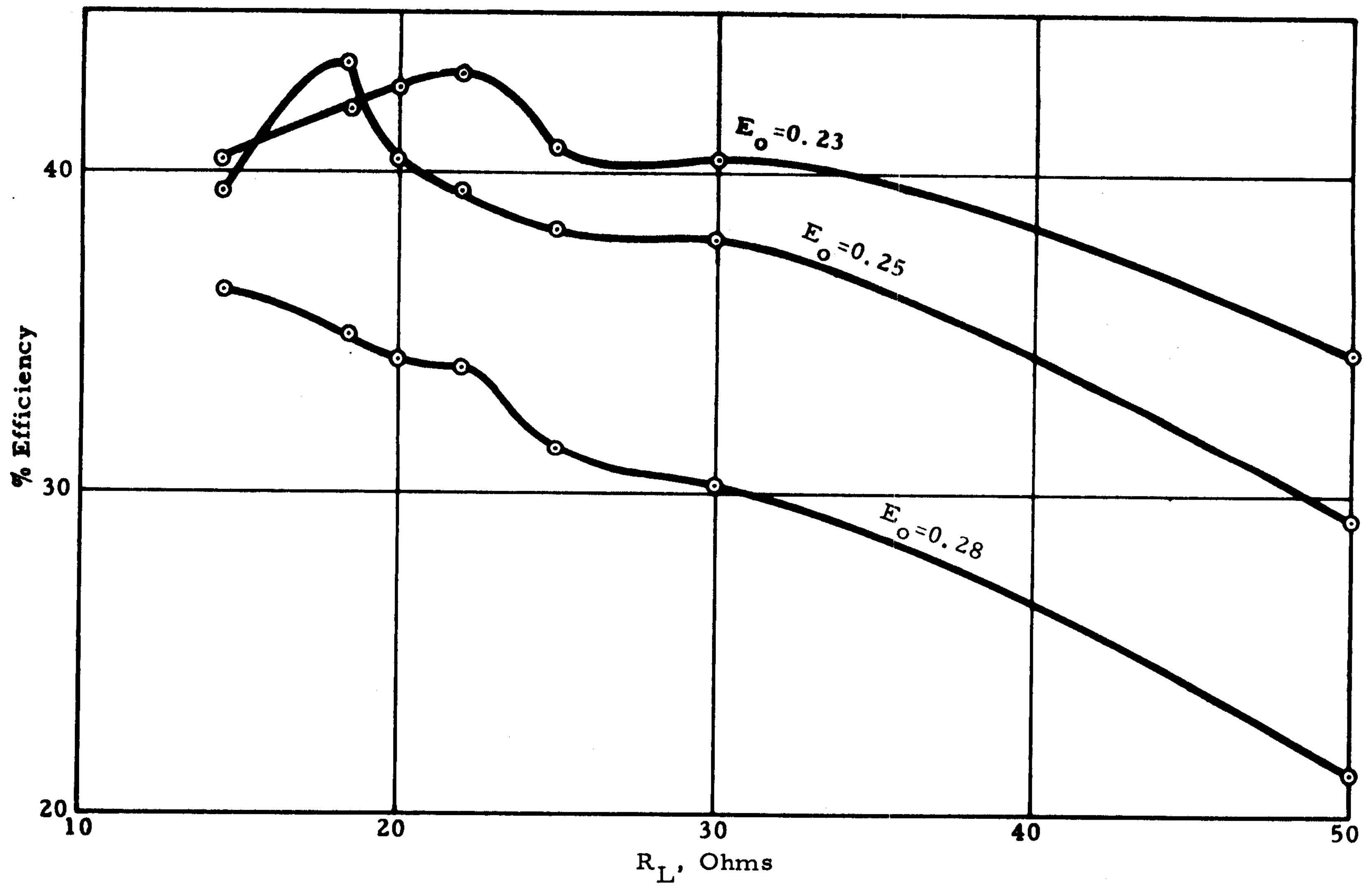


Figure 12. **Efficiency of the Tunnel Diode Inverter as a Function of Load Resistance (T4168-S1 Core, 56-Turn Primary of No. 18 Wire, 168-Turn Secondary of No. 26 Wire, Input Voltage as a Parameter)**

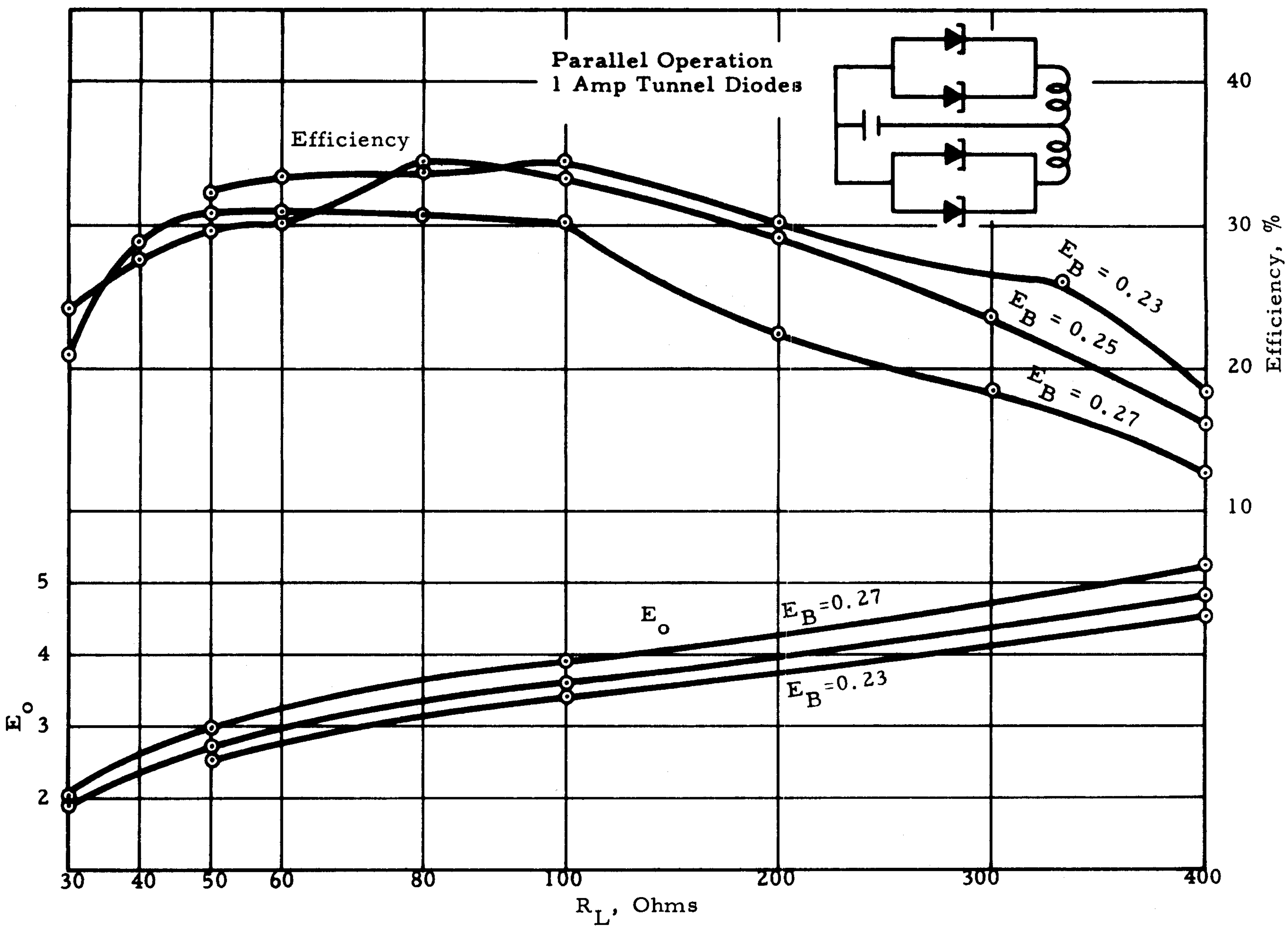


Figure 13. Efficiency and Output Voltage as a Function of Load Resistance when Two Tunnel Diodes are Operated in Parallel as a Single Switch and the Transformer consists of a 60-Turn Split Primary of No. 18 Wire and a 700-Turn Secondary of No. 26 Wire

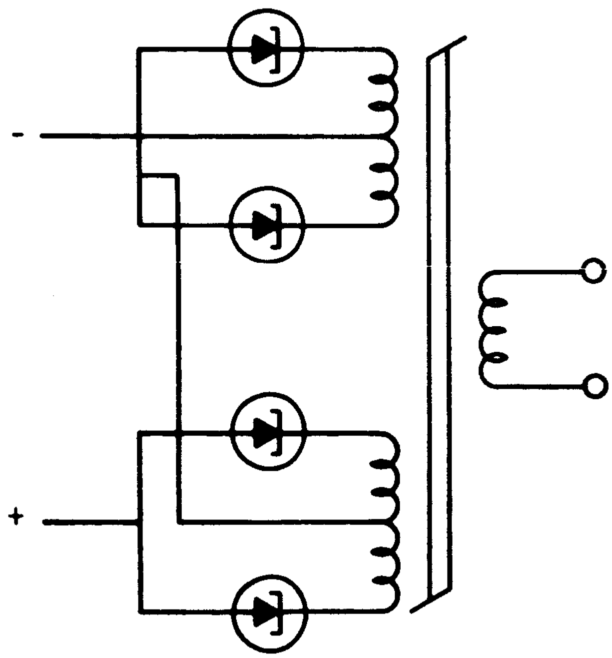


Figure 14. Circuit for Operating Tunnel Diodes in Series

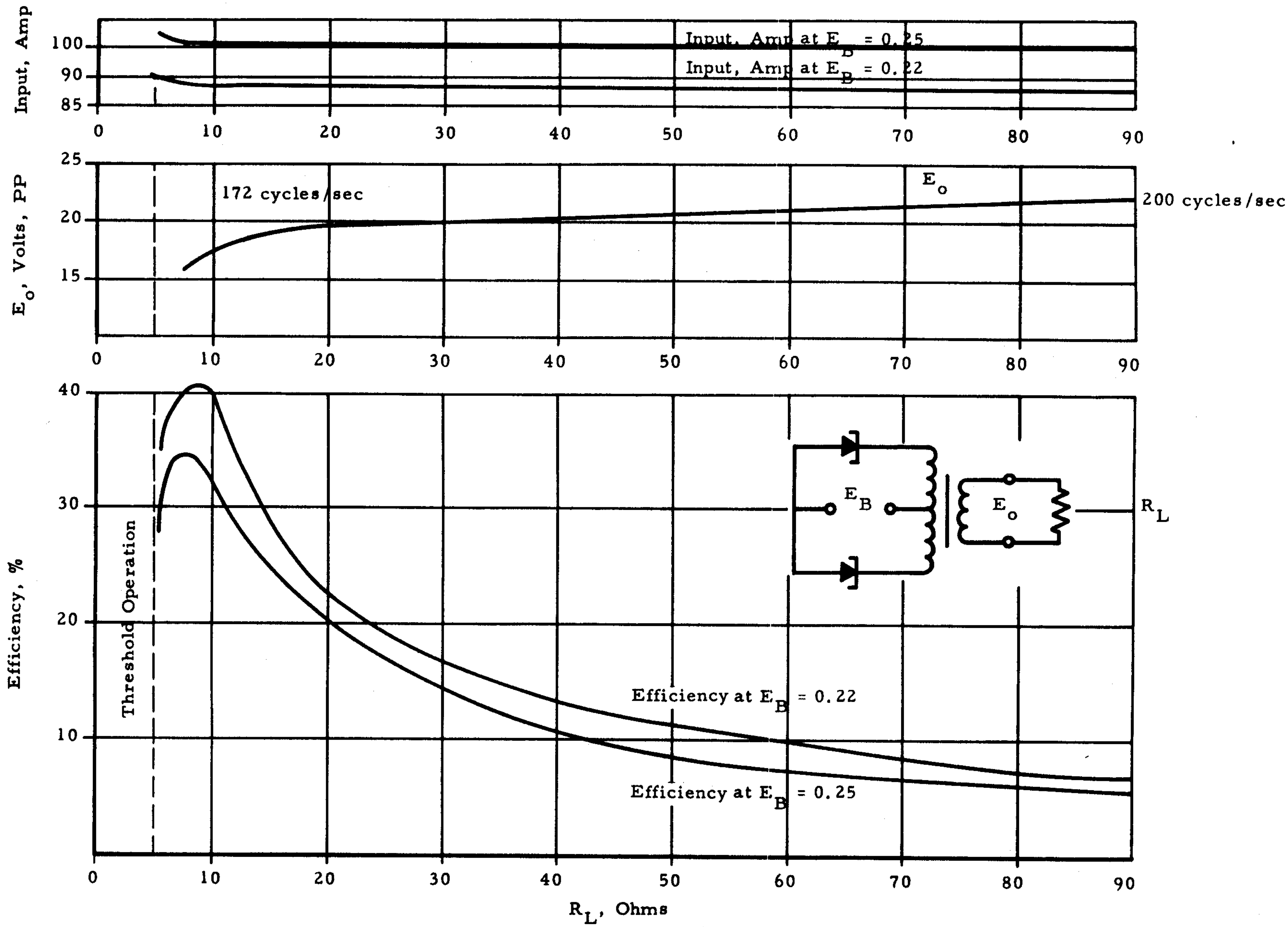


Figure 15. Experimental Results Obtained with 100-Amp Tunnel Diodes in the Inverter (Core 4T4180-S4, 8-Turn Center-Tapped Primary of 133,000 Circular Mil Wire, 200-Trun Secondary of No. 20 Wire)

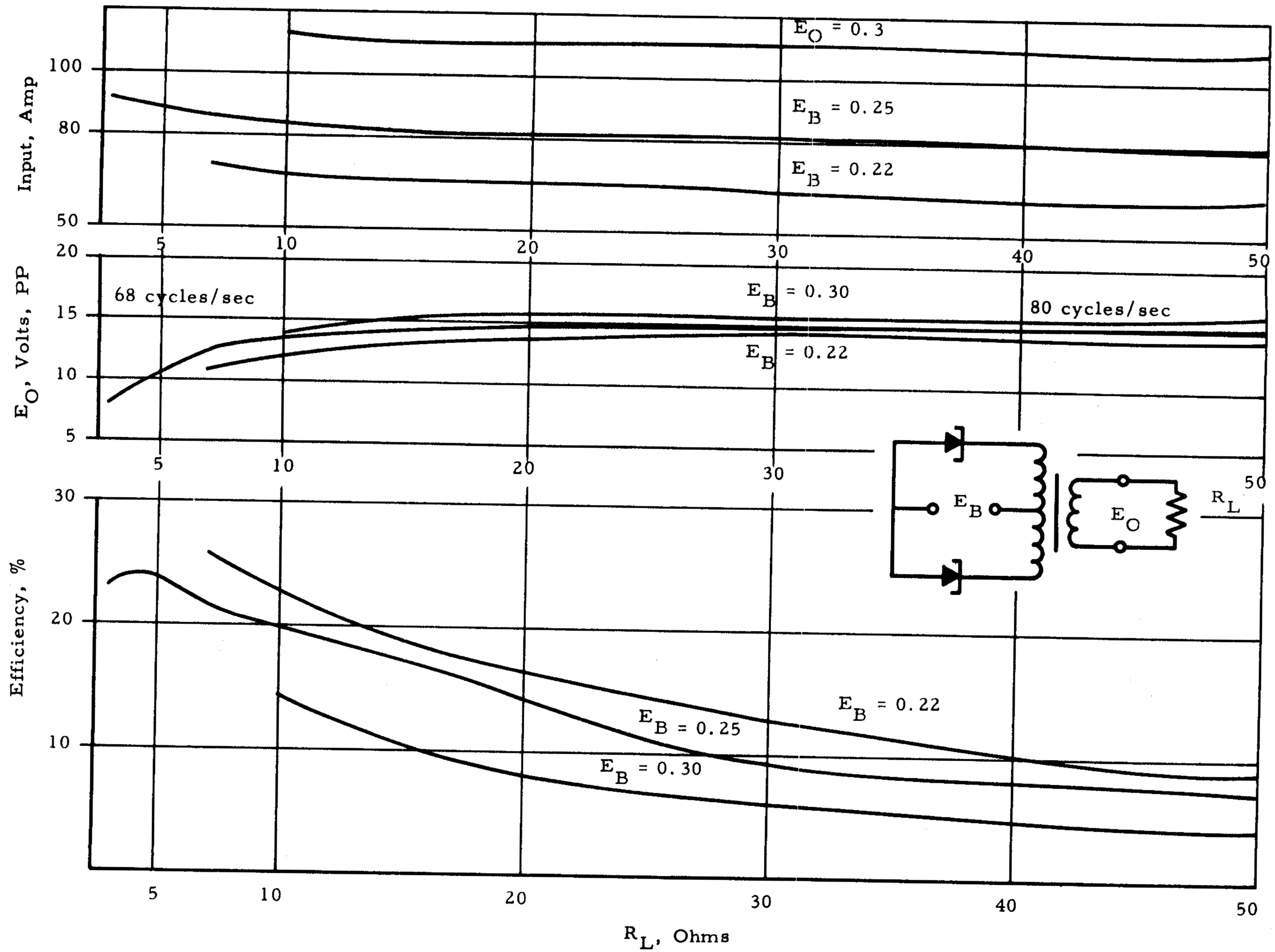


Figure 16. Experimental Results Obtained with 100-Amp Tunnel Diodes and a Second Transformer Design (Core 4T4180-S4, 20-Turn Center-Tapped Primary of 71,564 Circular Mil Wire, 415-Turn Secondary of No. 20 Wire)

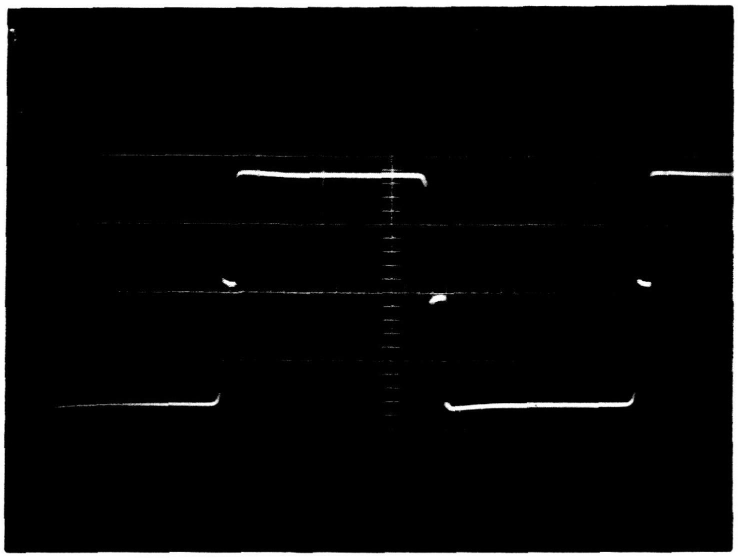


Figure 17a. Output Voltage of the 100-Amp Tunnel Diode Inverter Operating into an Infinite Load Resistance (Vertical Scale = 10 v/cm, Horizontal Scale = 1 millisec/cm, Input Voltage = 0.23 v)

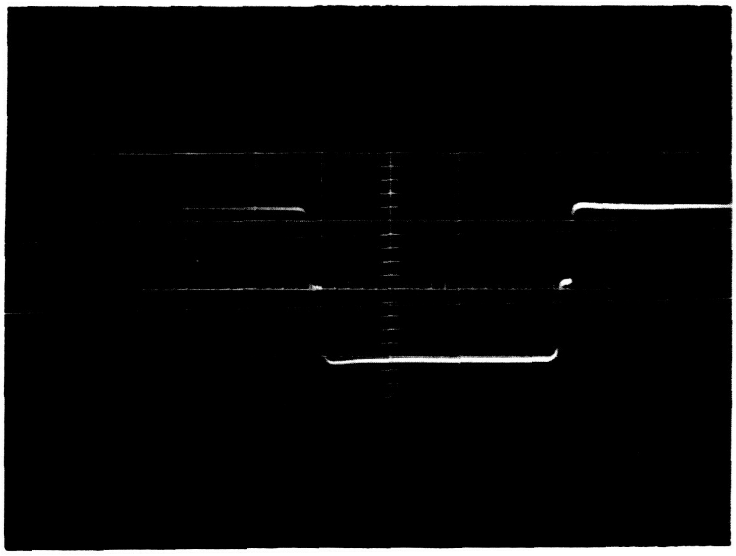


Figure 17b. Output Voltage of the 100-Amp Tunnel Diode Inverter Operating into a Load for Maximum Efficiency (Vertical Scale = 10 v/cm, Horizontal Scale = 1 millisec/cm, Input Voltage = 0.23 v)

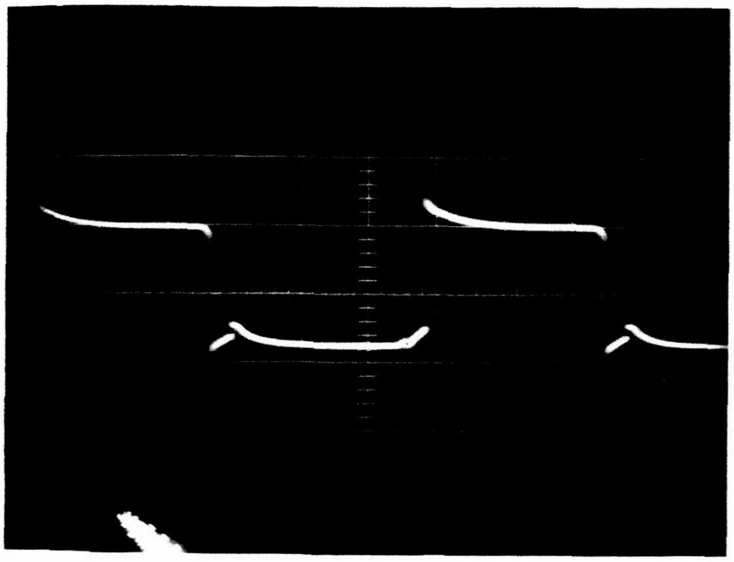


Figure 17c. Voltage Across the Tunnel Diode When Operated Under the Conditions of Figure 17b (Vertical Scale = 0.2 v/cm, Horizontal Scale = 1 millisec/cm, Zero Reference 1 cm Below Center of Reticle)

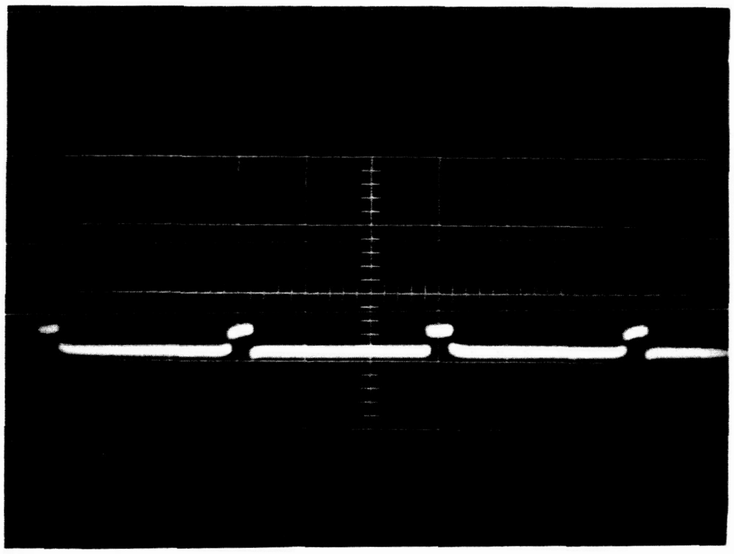


Figure 17d. Input Current When Inverter Operates Under Conditions of Figure 17b (Vertical Scale = 480 amp/cm, Horizontal Scale = 1 millisec/cm, Zero Reference 1 cm Below Center of Reticle)

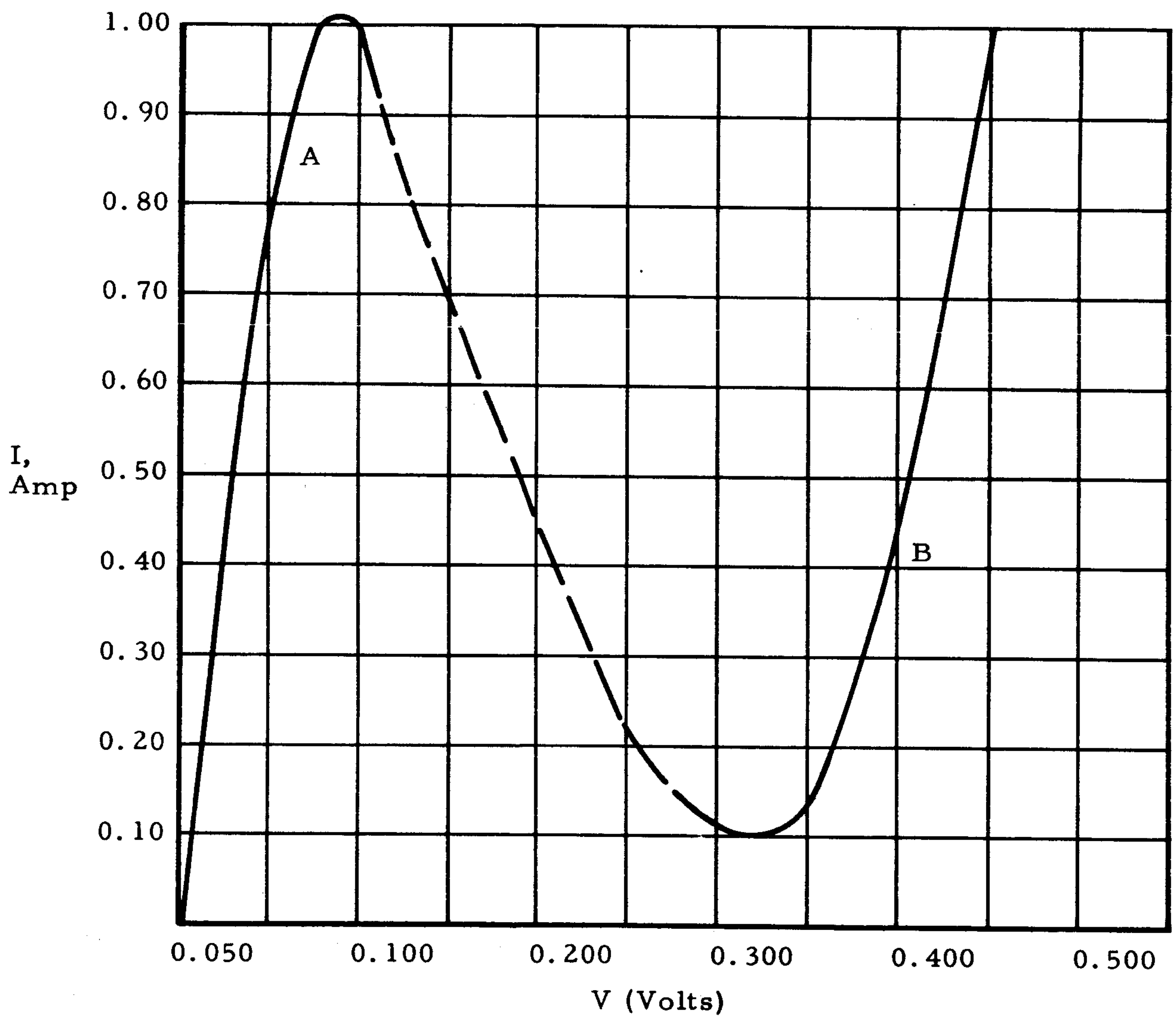


Figure 18. Characteristic Curves of 100-Amp Peak Tunnel Diode With (A and B are Diode Points for Maximum Efficiency)

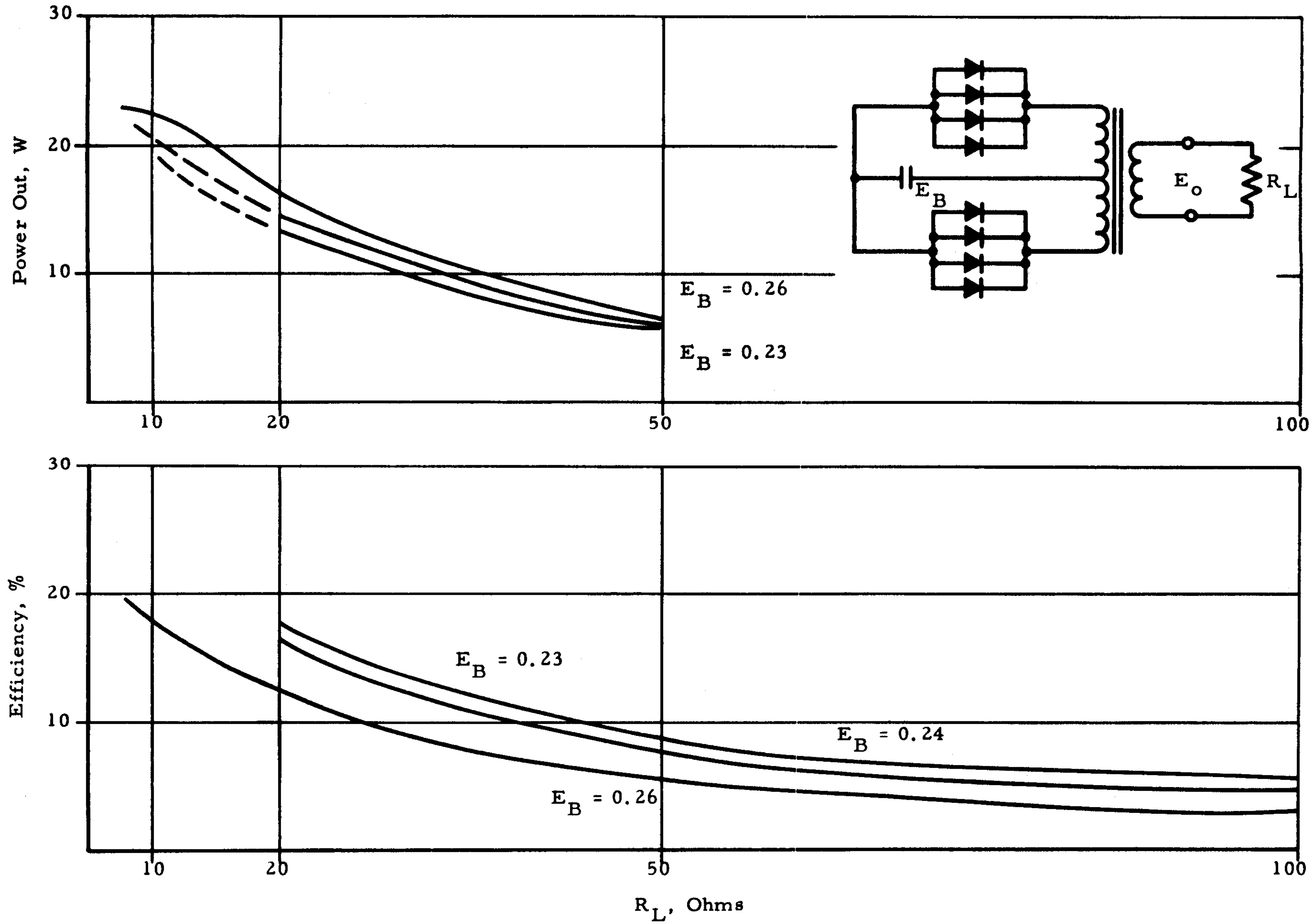


Figure 19. Experimental Results Obtained with the 400-Amp Input Tunnel Diode Inverter (Core CRA-65, 8-Turn Center-Tapped Primary of 494,000 Circular Mil Wire, 1500-Turn Secondary of No. 22 Wire)

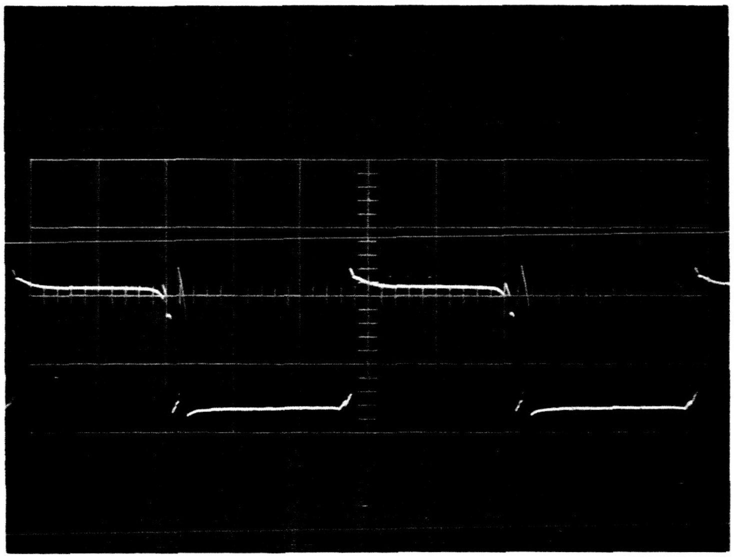


Figure 20. Voltage Across a Tunnel Diode as a Function of Time (Vertical Scale = 5 v/cm, Horizontal Scale = 2 millisec/cm, Zero Axis 2 cm Below Centerline of Reticle)